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# **COMPUTATIONAL NONLINEAR AEROELASTICITY**

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**Design and Analysis Methods Branch  
Structures Division**

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Final Report**

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14. ABSTRACT This report documents the culmination of in-house work in the area of computational modeling techniques for aeroelasticity. At the project onset, emphasis was given to the challenge of predicting flutter points for aircraft in the transonic regime. Methods based on bifurcation theory and reduced order modeling were developed and tested. This work helped to shape the activity of the aeroelastic community, and an international workshop in the subject area to be held in 2008 testifies to this achievement. Attention then turned to studying vehicles that might experience large structural deformations, such as high-altitude vehicles. Finally, computational methods have been investigated for the exploitation of aeroelastic interactions in the design of micro-air vehicles.					
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## Objectives

The goals of this task are the study of the multidisciplinary physics relevant to flapping-wing micro air vehicles (MAVs), and the development of computational tools by which these physics may be exploited in the design optimization of such vehicles. The fluid physics relevant to flapping-wing MAVs are nonlinear and include the formation, shedding, and convection of vorticity. The structural dynamics are likely nonlinear with respect to interactions with the fluid owing to the large deformations in the flapping wings. The structure might or might not also be inherently nonlinear due to geometric or material nonlinearities. Our contention is that MAV system performance will be sensitive to nonlinear interactions and that the development of practical flapping-wing MAVs with suitable levels of endurance and power efficiency will require that the physics of the system be represented to an unusually high level of fidelity during the design process.

As we work towards testing this hypothesis through time-consuming development of detailed modeling and optimization techniques, we are also pragmatically developing a framework with which we can study flapping-wing MAV behavior and design concepts using lower-fidelity techniques. In this way, we seek to understand leading-order behaviors and sensitivities, thereby exposing configurations likely to benefit from improved physical descriptions. We also recognize that, to achieve our objectives, numerous components of the research will exist (theoretical, computational, experimental), some of which are not possible to carry out in-house within the scope of the task. Thus, we have established a number of collaborations to form a reasonably comprehensive and coherent research strategy.

For MAVs, the research hypothesis we test is that the nonlinear interaction between a highly-flexible wing and the surrounding separated flow enhances the propulsive efficiency of the vehicle. We consider this to be a complex, time-periodic, system design problem, in that wings of inappropriate structural size and layout, and actuated at the wrong frequency and stroke pattern, will fail to take advantage of quasi-resonant behavior in the fluid-structure system. In this work, we focus on exploiting favorable nonlinearities using new computational tools that reveal essential physics.

We intend to apply our background in nonlinear analysis and limit-cycle oscillation prediction to achieve a fundamental understanding of how bird and insect wings behave aeroelastically and how these behaviors might be exploited productively in the design of flapping-wing MAVs. There are several objectives of this work:

1. Develop a structural design capability for MAVs assuming simplified aerodynamics and nonlinear structural dynamics. Understand the phasing relationships desired for efficient actuation of the wing mechanisms, and the role of structural flexibility in modifying these relationships. Determine in what ways structural flexibility can be advantageous, including weight penalties.
2. Formulate and implement strategies for computing time-periodic solutions of large systems of autonomous equations based on discretization of flow equations. Determine if it is then practicable to optimize these systems for numerous design variables. Understand the influence of sharp transients in the temporal response on the numerical efficiency of the scheme in comparison to other methods.
3. Develop and validate a capability suitable for the analysis of wing structures that are highly flexible and topologically complex.
4. Develop an optimal design capability for MAVs in 3-D based on the previous objectives, including flow physics necessary to capture properly the dynamic forces observed in biological flight. Investigate the changes in structure and optimal actuation that would occur for forward flight vs. hover.
5. Understand the role of structural flexibility in potentially increasing the propulsive efficiency of flapping wing flight. Determine if vibratory characteristics of the system, when actuated properly, can be amplified and used productively. Investigate the prediction and use of scaling laws, in an unsteady, low Reynolds number environment, for characterizing relationships between size, weight, speed, etc, that could be useful for defining mission profiles.

## Status

During the second year of the revised grant LRIR 99VA01COR, we have (1) completed initial development of a framework for simulating flapping-wing MAV behavior; (2) developed an analysis procedure for computing the sensitivities of system quantities with respect to variations in structural quantities for use in system optimization; (3) evaluated propulsively-efficient actuation patterns, enabled by the optimal tapering of a wing spar; and (4) explored the suitability of various CFD-based aeroelasticity methods for application to flapping-wing MAV flight and for design framework validation.

The MAV simulation framework currently incorporates linear methods for modeling the kinematics, aerodynamics, and structural dynamics of flapping-wing MAV flight and manages the physical coupling between these disciplines. Within this framework, we have explored the use of cyclic methods to exploit the character of flapping-wing flight. Next year, the design and simulation framework will be enhanced by optimizing the wing structure to achieve a power efficiency objective subject to a weight constraint and by adding higher-fidelity models.

We have also continued to transition previous research conducted under the auspices of this grant to other projects. These transitions, which have been funded by AFRL/VA as well as through other AFOSR grants, are described later in this report.

## Accomplishments and New Findings

We have completed initial development of a framework for simulating the steady-state behavior of flapping-wing MAVs. This framework combines a quasi-steady MAV aerodynamics model, a linear beam model, a simple fluid-structure interface, several time integration schemes, sensitivity computation, and an optimization tool. We will use this basic capability to identify leading-order behaviors, while simultaneously extending the framework with higher-fidelity modeling tools. For example, a vortex lattice method is being developed to better capture aerodynamic behavior and a nonlinear beam model is under development to better represent the structure.

With respect to the basic analysis capability, the aerodynamics model is designed to simulate characteristics of a fruit fly and treats the total force on the wing as a sum of components  $\vec{F} = \vec{F}_S + \vec{F}_R + \vec{F}_A$  where:

$$\begin{aligned}\vec{F}_S &= \frac{1}{2}\hat{k}\rho\|\vec{v}\|^2 C_L c \, dr + \frac{1}{2}\hat{i}\rho\|\vec{v}\|^2 C_D c \, dr \\ F_A &= \frac{\rho\pi c^2}{4} \left[ \left( \frac{\vec{v} \cdot \dot{\vec{v}}}{\|\vec{v}\|} \right) \sin \alpha + \|\vec{v}\| \dot{\alpha} \cos \alpha \right] dr \\ F_R &= C_R \rho \dot{\alpha} c^2 \|\vec{v}\| \, dr.\end{aligned}$$

Force coefficients  $C_L$ ,  $C_D$ , and  $C_R$  are taken from experimental data. The structural model uses a traditional linear Timoshenko beam finite element model and loads and displacements are interpolated between the fluid and structure using a simple sectional mapping. The gradient-based and DOE capabilities of the Vanderplaats R&D DOT and VisualDOC tools have been used for optimization. The equations of motion for the MAV dynamics are cast into the form

$$G \equiv \mathcal{A}_g X_g - \mathcal{B}_g F_g(X_g) = 0$$

and solved using a spectral element method. Here  $X_g$  is the state array of translations and velocities at each integration point over a flapping cycle of motion. The spectral element method that has been developed under this task is similar to the harmonic balance method but uses a local expansion and a non-uniform distribution of elements to better resolve transient behavior. For a  $Q$ -th order spectral element, the solution over each element is taken to be of the form

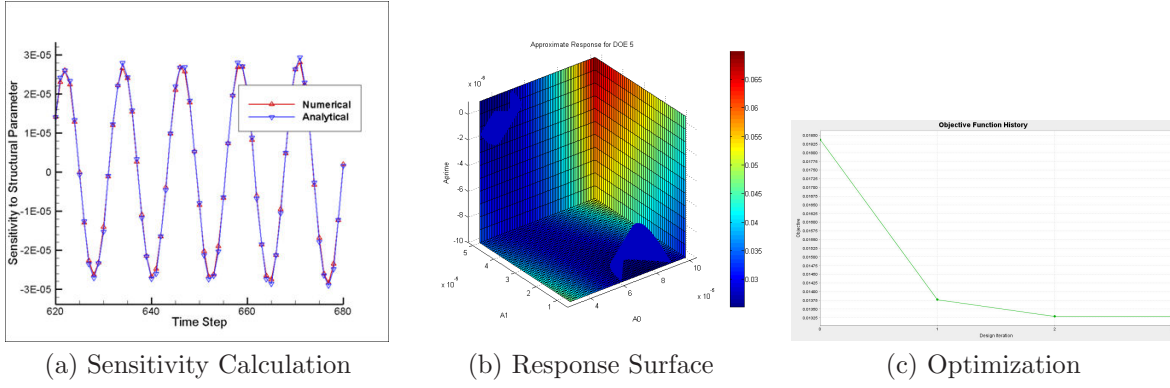


Figure 1: MAV Framework Results

$$X_g^n(\zeta) = \sum_{q=0}^Q X_g^n(\zeta_q) \psi_q^n(\zeta),$$

where  $\psi_q^n$  represents the Lagrange polynomial of order  $q$  in element  $n$ , the  $\zeta_q$  are the  $Q + 1$  zeros of the Lobatto-Legendre polynomials defined on the interval  $\zeta \in [-1, 1]$ , and  $X_g^n(\zeta_q)$  are the unknown nodal values placed at the  $\zeta_q$  for element  $n$ . For optimization, the sensitivities of a chosen objective function  $I$  to changes in the design variables  $\Lambda$  can be computed using either direct or adjoint analysis. The adjoint formulation is advantageous when there are a large number of design variables and few constraints.

We have used our MAV modeling framework to investigate the accuracy of the sensitivity computations and to explore preliminary optimization problems. Figure 1a shows a comparison of analytically and numerically-computed sensitivities of a notional objective function to a structural parameter. The beam was subjected to a sinusoidally-varying load applied to the wing tip and a measure of the integrated absolute displacements along the beam was used as the objective function. Figure 1b shows a response surface computed for the same objective function with the design variables controlling the character of the MAV flapping cycle. Figure 1c shows the variation in the objective function over the course of a gradient-based optimization about a point selected from the response surface.

Flapping wings undergo very large translations and rotations over the course of a flapping cycle. This motion represents a challenge for CFD-based modeling of flapping-wing MAVs as the discretized solution domain must be adapted to the motion of the embedded geometry. Mr. Aaron McClung and LtCol Raymond Maple at AFIT, with funding provided by this task, have investigated two leading strategies for managing large motion that are suitable for use in CFD: overset grids and unstructured remeshing. McClung and Maple developed a simplified model of a hawkmoth based on experimental data. Using FLUENT to represent the unstructured remeshing approach and Beggar the overset grid approach, it was determined that large rigid body motion could be handled more efficiently in Beggar than in FLUENT. In spite of a denser Beggar mesh, motion in the overset solver was resolved more than ten times faster than by the unstructured remesher. Additionally, the overset method maintained grid quality throughout the flapping cycle since the component mesh remained unchanged. Grid quality in the unstructured mesh was found to depend heavily upon the value of several parameters associated with the remeshing.

Drs. Paul Cizmas and Thomas Strganac, working at Texas A&M University with AFOSR funding under Grant Number FA9550-04-1-0174 and in collaboration with this laboratory task, have been developing a numerical method for conducting nonlinear aeroelastic analyses of wings where the wing undergoes large deformations that are of a magnitude on the order of the wing span [3]. They have used the Navier-Stokes equations model the fluid and nonlinear beam equations to model the structure. The method has been applied to the study of limit-cycle oscillation in the Goland wing, which is a thin, unswept, and untapered cantilevered wing. Through this work, they have demonstrated a robust grid de-

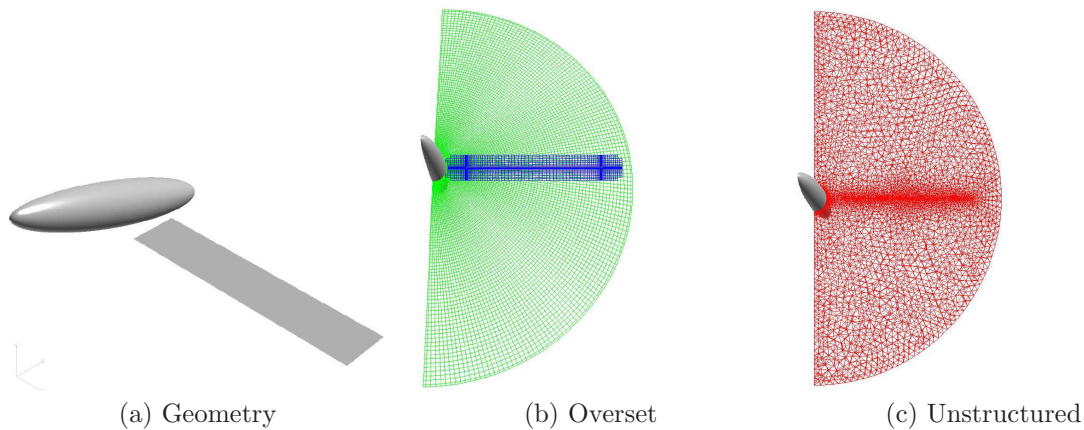


Figure 2: Hawkmoth Configuration Used to Explore Large Rigid Body Motion

formation strategy for large deformations and have shown that structural nonlinearities can have a strong effect on LCO response. We see possible application of this method to flexible flapping-wing MAVs. The grid deformation method, in particular, could be applied to higher-order aeroelastic modeling of MAVs.

In joint work led by Dr. Muhammad Hajj of Virginia Tech, we used high-order spectra to interrogate flight test data for nonlinear mechanisms of flutter and limit-cycle oscillation. In recent studies, we have used this method to explore the nonlinear mechanisms that drive LCO in a store-laden F-16 undergoing a wind-up turn and flutter of a flexible semi-span wind tunnel model of a high speed civil transport. Since we expect strong nonlinear behavior in flapping-wing MAV designs, we believe that this work will help us to identify the character of MAV nonlinearities and to build reduced order models that will encapsulate critical physics of tested specimens. A design process based on such reduced order models could be very important to the successful design of MAVs. Details are given in [4] and [5].

In joint work led by Dr. D. Michael McFarland of UIUC, we explored the application of nonlinear energy sink technology to the alleviation of transonic aeroelastic behaviors. Dr. McFarland was funded by this task to spend time this summer working at Wright-Patterson AFB so as to enhance the exchange of information with our research group. The AFRL is interested in this technology as a possible practical means of extending fleet readiness, and the potential increase in performance of aircraft that carry stores. We are also interested in this technology as a means for regulating nonlinear dynamic responses in MAVs. Details of the work are given in [7]. Dr. Ali Nayfeh of Virginia Tech, through funding provided by AFRL/VA's World-Class Visiting Scientist program, spent time at AFRL this summer to discuss examples of targeted energy transfer and control and of methods for approaching such problems.

## Supported Personnel

- Dr. Philip Beran (Principal Research Aerospace Engineer), AFRL/VASD
- Dr. Richard Snyder (Research Aerospace Engineer), AFRL/VASD
- Maj Greg Parker, Ph.D. (Aerospace Engineer), AFRL/VASD
- Capt Robert Walker (Aerospace Engineer), AFRL/VASD – AFIT M.S. graduate, March 2007
- Dr. Chris Chabalko (NRC Postdoctoral Researcher), AFRL/VASD – supported from March 2007
- LtCol Raymond Maple, Ph.D. (Assistant Professor), AFIT
- Mr. Aaron McClung (Ph.D. student), AFIT
- Capt Adam Tobias (M.S. student), AFIT – supported up to March 2007 graduation
- Dr. D. Michael McFarland (Research Associate Professor), UIUC



- Dr. Dean Mook (Emeritus Professor), Virginia Tech

The following individuals were funded by AFRL/VA's World-Class Visiting Scientist Program in support of this task.

- Dr. Oddvar Bendikson (Professor), UCLA – 4-week on-site presence
- Dr. Ali Nayfeh (Distinguished Professor), Virginia Tech – 1-week on-site presence
- Dr. Tony Palazotto (Professor), AFIT

## Publications

- [1] P. S. Beran, G. H. Parker, R. D. Snyder, and M. Blair. Design analysis strategies for flapping wing micro air vehicles. Conference Paper IF-109, IFASD, 2007. Presented at the International Forum on Aeroelasticity and Structural Dynamics, 18–20 June 2007, Stockholm, Sweden.
- [2] M. Blair, G. H. Parker, P. S. Beran, and R. D. Snyder. A computational design framework for avian micro air vehicles. AIAA Paper 2007-0763, AIAA, 2007. Presented at the 45th AIAA Aerospace Sciences Meeting and Exhibit, 8–11 January 2007, Reno, NV.
- [3] P. G. A. Cizmas, J. I. Gargoloff, T. W. Strganac, and P. S. Beran. A numerical method for non-linear aeroelastic analysis of wings with large deformation. Conference Paper IF-059, IFASD, 2007. Presented at the International Forum on Aeroelasticity and Structural Dynamics, 18–20 June 2007, Stockholm, Sweden.
- [4] M. R. Hajj and P. S. Beran. Identification of nonlinearities responsible for limit cycle oscillations of fighter aircraft. AIAA Paper 2007-1797, AIAA, 2007. Presented at the 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23–26 April 2007, Honolulu, HI.
- [5] M. R. Hajj, C. C. Chabalko, P. S. Beran, and W. A. Silva. Physical mechanisms related to identified nonlinear aeroelastic phenomena. Conference Paper IF-042, IFASD, 2007. Presented at the International Forum on Aeroelasticity and Structural Dynamics, 18–20 June 2007, Stockholm, Sweden.
- [6] A. McClung, R. Maple, and P. S. Beran. A comparison of overset methods and unstructured remeshing for modeling large rigid body motion. AIAA Paper 2007-327, AIAA, 2007. Presented at the 45th AIAA Aerospace Sciences Meeting and Exhibit, 8–11 January 2007, Reno, NV.
- [7] D. M. McFarland, P. S. Beran, Y. S. Lee, L. A. Bergman, and A. F. Vakakis. Transonic aeroelastic analysis including the effects of a nonlinear energy sink. AIAA Paper 2007-2016, AIAA, 2007. Presented at the 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23–26 April 2007, Honolulu, HI.
- [8] R. D. Snyder, P. S. Beran, G. H. Parker, and M. Blair. A design optimization strategy for micro air vehicles. AIAA Paper 2007-1853, AIAA, 2007. Presented at the 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 23–26 April 2007, Honolulu, HI.

## Interactions and Transitions

Technology developed within this Lab Task has been transitioned to several projects within the Aeroelastic and Design Technologies (ADT) Team. The ADT Team, led by Dr. Beran, is one of two teams in the Design and Analysis Methods Branch (Structures Division) and has 11 personnel. The primary recipient of technology is the Streamlined Stores Clearance (SSC) Product. Prior to the re-focus of this task on MAVs, this task developed technology in reduced order modeling and physical understanding in



the area of limit-cycle oscillations (LCOs). Subsequently, the technology was transitioned into the SSC Product, as was described in the FY06 report. The Real-Time Nonlinear Analysis System (RETINAS) 6.2 Project is completing this year, successfully achieving its goals of a high-speed analysis system to support testing. This capability will be validated over the next two years in a 6.3 flight test program, Nonlinear Interactive Clearance Environment (NICE) that is being executed at the Air Force SEEK Eagle Office (AFSEO), where aircraft/stores testing is conducted. The NICE project will complete the Spiral I SSC Product, delivering a new capability to AFSEO for accelerating their testing schedule. The technology used in this program will allow flight-test engineers to more effectively eliminate certain store configurations from consideration for testing, and for those fewer configurations that reach test, will enable engineers to visualize the instantaneous dynamics of the air vehicle structure and the modeled state of the airstream (e.g., visualize shock patterns on the wing surface by visualizing pressure), as well as to quantify the “goodness” of models derived prior to test based on real-time telemetry. This latter capability is of a prognostic nature, in that “peek-aheads” can be obtained through the fusion of model and test data. This process is of a rather generic nature, and should be applicable to future systems other than the F-16 system, which is the NICE validation platform.

The aeroelastic analysis tool developed to support NICE, OVERCAP, was completed in Oct 2006. The ADT team worked closely with the contractor team (Lockheed Martin and ZONA) to develop this fast tool for complex geometry from the underlying analysis capability, CAPTSDv, developed by NASA LaRC, whose applicability to LCO the team had previously studied in this task. In addition to F-16, OVERCAP has recently been applied to SensorCraft (FLTC 3), Global Hawk (requested by ASC), and will be used by Lockheed to help assess different tail locations for a fast access to space vehicle (FAST) that is being conceptualized. It is important that this vehicle be free from destabilizing aeroelastic phenomena throughout the transonic regime, which might be triggered by certain tail locations.

Clearly, the original work done with CAPTSDv has led to a breadth of relevant applications. Another potential application is in the area of LCO management. We worked with UIUC (Dr. McFarland) last summer to examine the integration of nonlinear energy sink (NES) technology into CAPTSDv for the purpose of developing NES systems scaled to full aircraft size. Dr. McFarland continued this work this summer, and it is likely that his findings will favorably impact an STTR project (Phase I) on LCO management awarded to NextGen and NES Tech/UIUC (Dr. Bergman).

In the area of MAVs, a 6.2 program was initiated from the Chief Scientist’s Independent Research Fund (CSIRF) to develop a flapping rig by which structural wing designs developed in this task could be tested to help validate the design procedures and their associated physical models. This 2-year \$70K program will be carried out in-house, in collaboration with AFIT, who will supply key equipment, needed experience, and student assistance. In partnership with the CSIRF project, this lab task provides an MAV Aeroelasticity capability required by the Agile Micro Sensor Product (FLTC 3.3.1.9).

## New Discoveries

- No patents have been awarded

## Honors and Awards

- Dr. Snyder, Perkins Award Finalist (2006-2007)